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TECHNICAL PAPER prepared for Thermionic Conversion Specialists Conference sponsored by the Institute of Electrical and Electronics Engineers

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ABSTRACT

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The emittance of small cavities electrically disintegrated in tungsten and molybdenum is measured with a disappearing-filament pyrometer. Cones and cylinders are studied. If proper safeguards are taken, cavities such as these are reliable targets on which to sight pyrometers when metal surface temperature is desired. The fabrication method yields cavities of satisfactory reproducibility. The emittance results are compared with analytical expressions and the latter are shown to be of very limited value except for deep, isothermal cavities.

Author

INTRODUCTION

The performance of thermionic converters is strongly dependent on emitter temperature. An accurate determination of emitter surface temperature by optical pyrometry requires a target of known emittance value. The emittance, and hence the absorptance, must be near unity, so that stray radiation from other hot sources and incident on the target is absorbed rather than reflected into the pyrometer. Refractory metals yield surface emittances[1,2] that are usually less than 0.5; however, deep holes drilled in any opaque material can provide emittance values near unity. Cavity design is a fairly simple task as long as the material is isothermal; frequently, however, this is not the case because refractory metals are poor thermal conductors, particularly at elevated temperatures where large thermal flows often exist. The resulting nonuniformity of temperature along the walls introduces uncertainty into the target emittance value and, hence, into the surface temperature evaluation. Therefore, cavity depth must be kept within certain bounds.

Since the rear walls of a cavity usually possess the largest and most uniform emittance values, this study is confined to pyrometer sightings that are along or close to the cavity axis. Interest is further restricted to spectral emission, since wide band (heat) detection apparatus is normally not selected for highly accurate temperature measurement of small objects.

Cavity emittance requires a fuller description if confusion is to be avoided. By current convention, surface emittance ϵ is the ratio of the radiant energy emitted by an arbitrary surface to the radiant energy emitted by a blackbody when both sources are at the same temperature. Cavity emittance ϵ_c is a similar ratio for an imaginary plane stretched across the opening of the cavity; the energy beamed towards the pyrometer is composed of both emitted and reflected light from the surface being viewed. For other than relatively deep cavities, the energy streaming from the wall to the pyrometer is not uniform from one surface-area increment to the next, although the surfaces themselves may be isothermal. This gives rise to a local cavity emittance ϵ_a, which has been expressed analytically[3] for cylindrical cavities possessing diffusely (Lambert) emitting and reflecting surfaces. Most analytical approaches[4,5,6,7] yield an overall cavity emittance ϵ_c.

While interest here is confined to viewing along or close to the cavity axis, the directional radiation characteristics of the surface itself can have a pronounced effect on the value of cavity emittance.[4,5] However, nearly all analytical expressions for cavity emittance consider the surfaces to be perfect diffusers. Williams[8] describes the merits and weaknesses of several analytical methods that are popular. More recently, Kelly and Moore have presented a review[9] of the various general methods that have been employed for deriving equations for cavity emittance. For cylindrical cavities, they show several expressions[3,7] that provide a good fit to their experimental data, which were confined to length-to-diameter ratios of 0.25 to 1.0. The purpose of their work was similar to the present paper, the significant difference being their concern for diffusely reflecting walls.

The aforementioned information is helpful, but it provides quantitative values of ϵ_a and ϵ_c for special cases only. Herein, several of the analytical formulations are compared with the experimental results obtained from electrically disintegrated cavities in tungsten and molybdenum.

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DESIGN CONCEPTS

The following features are desirable for a cavity drilled into a surface so that its temperature can be measured by pyrometry:

(1) Target-area emittance near unity
(2) Isothermal walls
(3) Target area of uniform radiance
(4) Target area of ample size
(5) Emittance constant with time
(6) Reproducible in manufacture

The aforementioned items are in many ways contradictory. If the surface containing the cavity is freely radiating to space and heat flow within the metal is unidirectional, temperature gradients ranging from 20° to 80° C/cm can occur. These figures are for a 2000° K tungsten surface; the four-fold range in values is related to the surface roughness and, hence, total emittance. Gradients can be larger or smaller when mass transport (e.g., electron cooling) is present. In order to concurrently satisfy items (1), (2), and (3), the cavity entrance must be small; however, if the target diameter (fig. 1) is too small, accurate pyrometer sightings cannot be obtained.

The drilling process produces two separate effects: the surface is roughened, and the material is subjected to lattice distortions. Bennett[9] shows that both have a pronounced effect on the magnitude of surface emittance and on the specularity of the reflected radiation. With proper annealing the radiation characteristics of the surfaces undergo change and finally become fairly stable.

Cavities must be reproducible in manufacture if ϵ_c data for a given cavity are to be of general utility. Reproducibility requires that tolerances of the gross-cavity dimensions are small and that surface roughness and damage do not vary from one surface element to the next.

APPARATUS

Holes were drilled into the ends of 3/8-inch-diameter tungsten and molybdenum rods (figs. 2, 3, and 4). Each rod was induction-heated in a vacuum environment of 10^{-6} torr or lower. The entire polished rod end containing the cavities radiated to "space." Front-surface and cavity temperature readings were obtained with a disappearing-filament pyrometer having an effective wavelength λ of 6530 Å. The view was along the cavity axis and through a window that had a remotely operated shutter which kept contaminants from reaching the window. Multiple reflections between window and rod end were minimized by locating the window normal slightly off-angle to the axis of the rod (fig. 3). Care was taken to ensure the capture of nearly all stray radiation by chamber walls and induction coil.

Drilling by electrical disintegration yielded holes of nearly uniform surface texture for all surfaces. The drilling technique produced shallow pocks with the rim of each pock touching its neighbors. Roughness depth was about 0.001 cm. The cones and cylinders fabricated in tungsten are shown along with dimensions in figure 4. The cavities were out-of-round by approximately 0.002 cm. The radius of curvature was about 0.005 cm for the cone apexes and for the corners of the cylinders. Frequent dressing and replacement of the electrodes used in the drilling process were required to attain these tolerances.

The pyrometer was a manually operated and commercially available instrument. Temperature readings when viewing large uniformly bright targets contained errors of approximately 5 degrees. Reproducibility of brightness matches was about 2 degrees for large targets. Unpublished work at this laboratory has shown that errors in measurement can be anticipated when the target diameter becomes smaller than five times the filament diameter. To achieve this minimum error-free target diameter W at the bottom-center of a cylindrical cavity, the cavity diameter D must be sufficiently large so that outermost rays emanating from the target and inci-

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dent on the pyrometer entrance are not blocked by the cavity lip (fig. 1). For a length-to-diameter ratio of 6 and a distance d of 40 cm, D must be 25 percent larger than W for the subject pyrometer.

PROCEDURE

Computation of cavity emittance ϵ_c assumes that the normal emittance ϵ_1 of the polished face of the rod is known.[10] The true temperature T of the front face of the rod can be obtained from the Wien equation

$$\frac{1}{T} = \frac{\lambda}{C_2} \ln(\epsilon_1 \tau) + \frac{1}{S_{B,1}} \tag{1}$$

where $S_{B,1}$ is the pyrometer-indicated temperature of the surface and τ is the window transmission. Likewise, the true temperature of the front-face of the rod is

$$\frac{1}{T} = \frac{\lambda}{C_2} \ln(\epsilon_c \tau) + \frac{1}{S_{B,2}} \tag{2}$$

where $S_{B,2}$ is the pyrometer-indicated temperature of the cavity after substraction of ΔT, the estimated temperature difference between the backwall of cavity and the front-face of the rod. Wherever differences in the emittance of various surfaces of a given cavity were being examined, ϵ_c of equation (2) was replaced by ϵ_a, the local cavity emittance.

Equating the two expressions for $\frac{1}{T}$ yields

$$\ln \frac{\epsilon_c}{\epsilon_1} = \frac{C_2}{\lambda} \left(\frac{1}{S_{B,1}} - \frac{1}{S_{B,2}} \right) \tag{3}$$

RESULTS AND DISCUSSION

The estimated temperature difference between front and back surfaces of the cavities ranged between 0 and 15 degrees. The largest values were associated with the large conical cavities for tungsten operated near 2200° K. At this temperature, a ΔT of 15 degrees corresponds to a change of about 0.06 ϵ_c units (eq. (3)).

A fairly deep cylindrical cavity (fig. 4, hole 14) was found to be of uniform brightness across the back surface. Such a target should provide measured ϵ_c values independent of distance and observer; therefore, hole 14 was used to establish the reproducibility and accuracy of the ϵ_c data. Figure 5 shows the results of numerous readings by each of two observers. Reproducibility of each observer deteriorates badly when the cavity-to-filament-diameter ratio becomes smaller than 3.2. Also, the ϵ_c values obtained by the two observers are shown to decrease when the pyrometer is placed too far from the cavity. Both observations conform to the remarks about minimum permissible target diameter made in the APPARATUS section of this report. Accuracy largely depends on reproducibility of readings, observer judgment, pyrometer calibration error, and uncertainty in emittance of the front face (ϵ_1 of eq. (3)).

The annealing (aging) process produced interesting developments. Whisker growth occurred on the cavity surfaces during the initial heat of the molybdenum rod. The growth was rapid, occurred below 1400° K, and resulted in a very marked lowering of cavity emittance. The rod was removed, cleaned by gentle scraping, and returned to the vacuum vessel. On further heating, whiskers did not develop. Whisker diameter was only about 0.001 cm; hence, this nuisance cannot always be readily detected.

Emittance data were obtained for molybdenum cavities during the annealing process. While the temperature underwent numerous cycles, one heat of 2000° K was maintained for a day. One cylindrical hole had the same dimensions as the tungsten cavity used for figure 5; the other two cavities were also of 0.04 cm diameter, but they had length-to-diameter values of 3.74 and 2.95, respectively. Initially, the back wall of each hole appeared to be of uniform brightness. As aging progressed, the surface structure of the shallowest cavity could be observed through the pyrometer optics. The area of uniformly bright surface became so small that temperature measurements were very difficult to obtain. The intermediate hole underwent the same process, but the effect was smaller. By the time a stable or near-stable surface condition was attained, the bottom of the deepest hole had lost a little of its uniformity; however, temperature readings had accuracies comparable to those for the tungsten cavity. This latter molybdenum cavity (L/D, 4.85) provided a cavity emittance ϵ_c of 0.946 at temperatures from 1300° to 2200° K.

On removal from the vacuum vessel, the molybdenum cavity surfaces were found to be shiny. These surfaces had originally appeared lusterless. The pock marks were still present, but on a more local scale the surfaces appeared to be very smooth when viewed with a microscope. A similar but less noticeable effect was observed for tungsten, which was aged at about 2350° K for a day. The tungsten rod may not have been as thoroughly annealed and cleaned by heating as the molybdenum rod.[11,12] However, changes of tungsten values ϵ_c with time were not observed for the considerable number of hours required to obtain the data presented herein. The aged roughened area (no. 15 of fig. 3) yielded a surface emittance of 0.5. For an aged, electrically disintegrated molybdenum surface, ϵ was near 0.4.

The largely specular behavior of the reflections observed for flat, electrically disintegrated surfaces implies that experimental ϵ_c data will correlate poorly with analytical studies based on diffusely reflecting surfaces. On the basis that ϵ_c equals cavity absorptance α_c, the reflection behavior of the metal surface itself can be illustrated by example. A light beam of finite cross-sectional area traveling parallel to the axis and into a conical cavity strikes a wall and is partially absorbed. For a perfectly specular surface the remaining light is reflected further into the cavity when the total cone angle is less than 90°. Had the surface been a diffuse reflector, a portion of the light, on its first contact with the wall, would have been reflected out of the cavity entrance. In the case of a cylindrical cavity, a specularly reflecting end-disk-surface reflects axially incident light back along the path it entered. Cavity effect is minimal.

As expected from the preceding discussion, the experimental ϵ_c data for cones correlate poorly with analytical results[6] based on diffuse surfaces (fig. 6). To utilize the largest possible area for a filament-target brightness match, one desires to sight the pyrometer on the center of the cavity. This presents problems in the case of cones because of the difficulty in fabricating a pointed bottom. Cones having a cone angle larger than 30° were observed to have areas of reduced brightness at and near the apex. This area had to be avoided when conducting a brightness match. Furthermore, these two cones produced a low-intensity annular surface on the inner periphery of the cone. While a cone angle of less than 25° is preferred for electrically disintegrated tungsten, fabrication of small deep cones requires considerable skill.

Local cavity emittance data for tungsten cylinders are shown on figure 7. Experimental data are compared with an analytical expression by Sparrow et al.[3] for perfect diffusers. For a given value of L/D, the analytical expression yields ϵ_a values that are smallest near the center and largest near the periphery. For any given length-to-diameter ratio, all the experimental data lie below the analytical values. This is explained by the specularity of reflection of the tungsten surfaces. Figure 7 also shows the change of measured emittance as the ratio of cavity diameter to filament diameter is varied. Since these cavities are of the same diameter, a dual abscissa is provided on the figure. The deepest cavity (L/D, 3.1) exhibits a uniformly bright target area and measured emittance is independent of distance and observer. These results compare favorably with those of figure 5 for cavity-to-filament diameter ratios of 3.2 and larger. At length-to-diameter values less than 3, brightness nonuniformity of the end disk was easily detected; however, at small values of d the minimum error-free target diameter W included only a small fraction of area at the center of the disk. This area was of nearly uniform brightness, hence the ϵ_c values at small values of d were independent of distance d. As d was gradually increased from a value of 50 cm, brightness matching became progressively more difficult because the outer region of the minimum error-free target area became brighter. The resulting measured emittance increases and the reproducibility decreases. These results show that brightness nonuniformity of the end disk is objectionably large for these shallow cavities.

Experimental values of local cavity emittance obtained for the center of the end-disk are summarized in figure 8. The ϵ_a values are for a target diameter W that is small compared to the cylinder diameter D. Results by D. F. Edwards,[5] using the DeVos[4] analysis for a nondiffuse surface, are included. These analytical results are suspect at low values of length-to-diameter ratio where the experimental data show the end disk to be of nonuniform brightness. Also, the DeVos computations are only for a surface emittance ϵ of 0.4; however, four different surfaces were examined. One was a perfect diffuser, and the other three surfaces had vary-

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ing fractions of the reflected energy distributed between diffuse and perfectly specular modes. The ϵ_c values for a perfect diffuser is in such close agreement with diffuse surface results of Sparrow, et al. (fig. 8) that they are not shown. The DeVos curve shown in figure 8 represents a surface somewhat less specularly reflecting than a highly polished refractory metal surface. The molybodenum and tungsten data are self consistent and both are shown to correlate well with the DeVos surface; it must be stressed, however, that the properties of the referenced surface are very arbitrary. (The most highly polished DeVos surface yielded much lower ϵ_a values than those shown here.)

Data obtained from all the cavities of figure 4 conformed to the experimental results that have been discussed. Reproducibility of fabrication of these small cavities appears satisfactory.

CONCLUDING REMARKS

Small cones and cylinders electrically disintegrated in refractory metals provide satisfactory targets on which to sight pyrometers if the cavities are selected with considerable care. Analytical expressions for ϵ_c are of little value (except for nearly black cavities) unless the directional distribution of the reflected energy is known.

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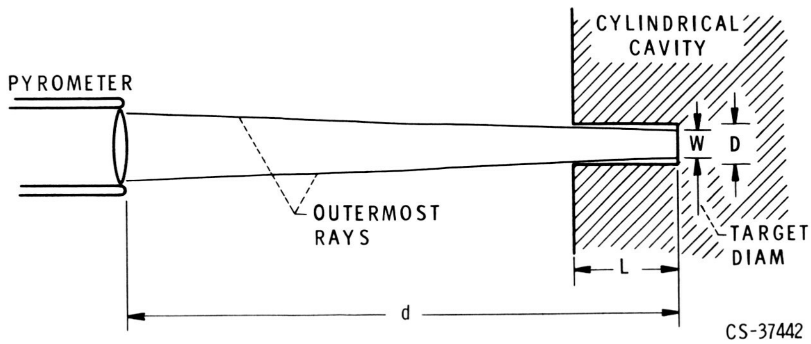

FIGURE 1. - OPTICAL PYROMETER SIGHTED ON A TARGET; W, MINIMUM ERROR-FREE TARGET DIAMETER OF THE PYROMETER AT DISTANCE d.

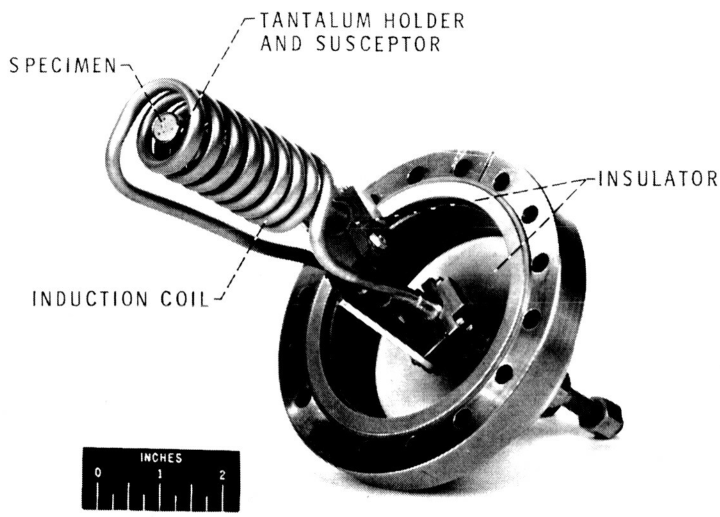

FIGURE 2. - TUNGSTEN SPECIMEN MOUNTEDIN COIL.

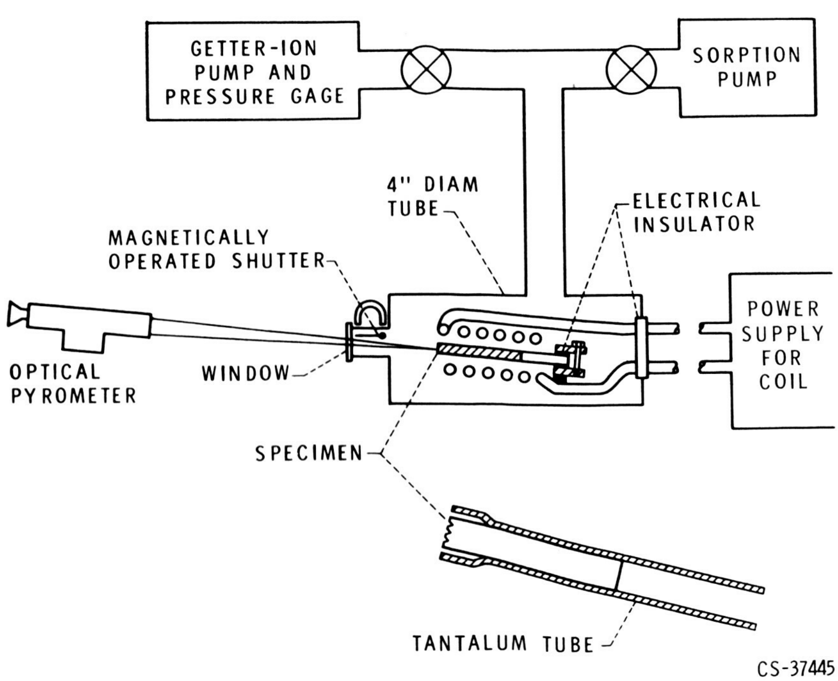

FIGURE 3. - APPARATUS.

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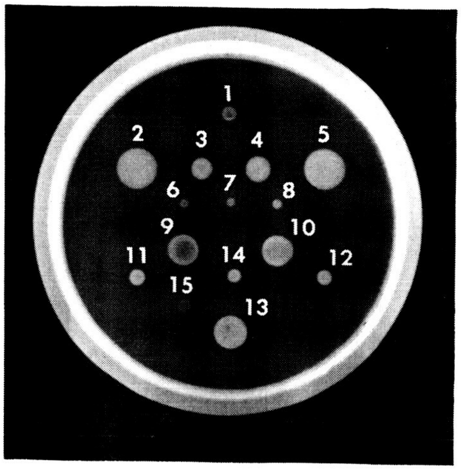

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CYLINDERS

	DIAM (MM)	L/D
6	0.27	0.80
7	.27	1.55
8	.30	2.39
14	.40	4.85
1	.49	0.85
11	.50	2.00
12	.50	3.10
9	1.00	1.04
10	1.00	2.06
13	1.00	3.10

CONES

	DIAM (MM)	ANGLE (DEG)
3	.80	42
4	.90	24
2	1.40	34
5	1.40	18

15 CONTROL SURFACE (ROUGHENED BY DRILL)

FIGURE 4. - HOLE DIMENSION OF TUNGSTEN SPECIMEN; ROD TEMPERATURE, 1500° K.

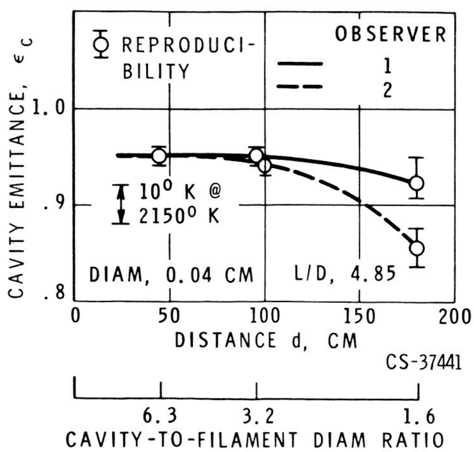

FIGURE 5. - EMITTANCE ERROR OF CYLINDRICAL TUNGSTEN CAVITY BECAUSE OF A TARGET AREA WHICH IS TOO SMALL RELATIVE TO PYROMETER OPTICS; TEMPERATURE, 1500° TO 2200° K.

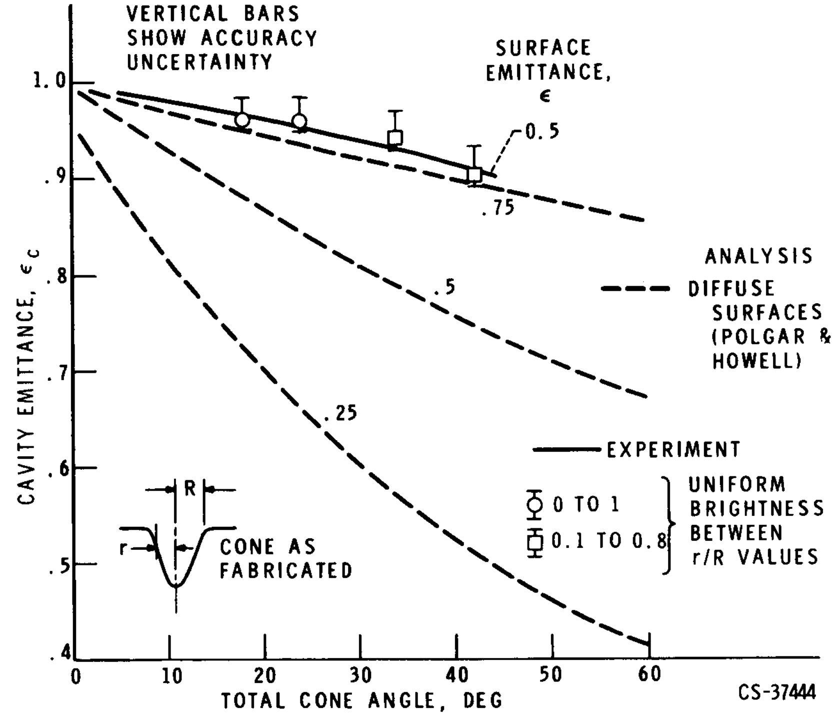

FIGURE 6. - EMITTANCE OF CONES. EXPERIMENTAL DATA ARE FOR TUNGSTEN CAVITIES WITH WALL TEMPERATURES OF 1500° TO 2200° K. PYROMETER WAS SIGHTED ON AREAS OF UNIFORM BRIGHTNESS. (ANALYTICAL RESULTS ARE FROM REF. 6.)

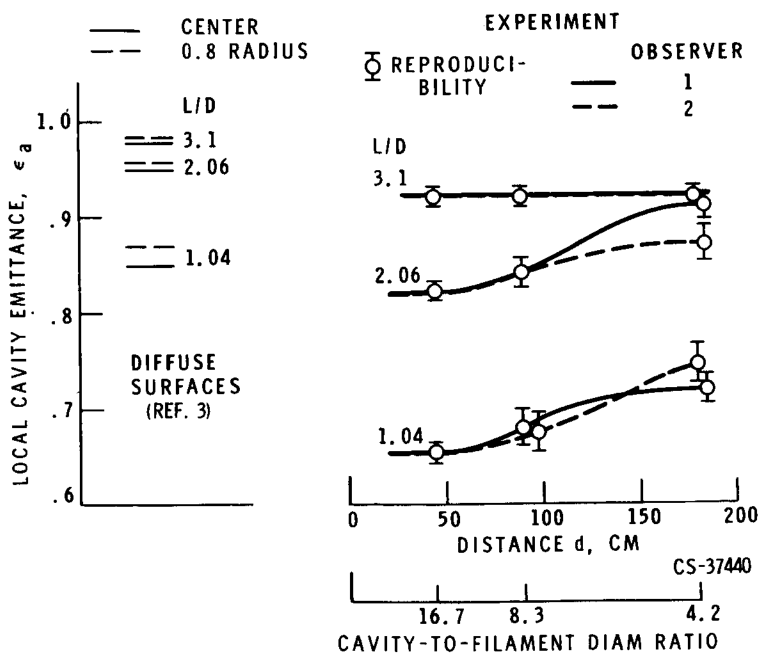

FIGURE 7. - LOCAL CAVITY EMITTANCE OF CYLINDERS FOR A SURFACE EMITTANCE OF 0.5. EXPERIMENTAL DATA FOR TUNGSTEN CAVITIES VIEWED ALONG THE AXIS. THE ANALYTICAL RESULTS SHOW AT EACH VALUE OF L/D THE VALUE OF ϵ_a AT TWO LOCATIONS ON THE BACK WALL.

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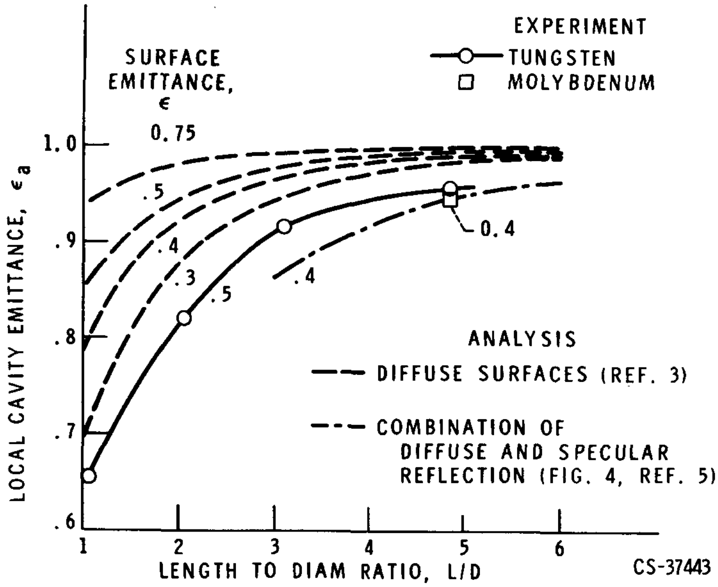

FIGURE 8. - LOCAL CAVITY EMITTANCE EVALUATED AT THE CENTER OF BACK WALL OF CYLINDRICAL CAVITIES. EXPERIMENTAL DATA ARE FOR CAVITIES WITH WALL TEMPERATURES FROM 1500° TO 2200° K.